SEX ESTIMATION FROM THE GREATER SCIATIC NOTCH OF THE HUMAN PELVIS: A GEOMETRIC MORPHOMETRIC APPROACH

by

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ABSTRACT

It is widely agreed that the human pelvis holds the greatest degree of sexual dimorphism and is the most useful bone for estimating sex in skeletal remains. It is also commonly believed that the greater sciatic notch holds a great deal of sexual dimorphism and can be used to estimate sex. Yet despite the crucial nature of estimating sex from skeletal remain when creating a biological profile, methods considered common today rely rather heavily on the experience of the anthropologist and on the presence of more complete innominate bones. Following earlier research by the author, this project examines the usefulness of two forms of geometric morphometric (GM) approaches to estimating sex from the portion of the innominate most likely to survive over time, the greater sciatic notch. These methods, originally tested on American White and American Black samples from the Terry Collection at the Smithsonian Institution, have now been applied to a Mexican sample from skeletal collection at the School of Medicine, National Autonomous University of Mexico (UNAM). The first GM approach uses a 3D digitizer to collect the coordinate points of three landmarks on the greater sciatic notch; the most anterior point on the posterior border near the posterior inferior iliac spine, the base of the ischial spine, and the deepest point of the notch. Geometric dimensions are calculated from these coordinate points and constitute one data type for GM analyses. The second type of data is formed by coordinate data of semilandmarks that describe the shape of the greater sciatic notch. Multivariate statistics were used to examine the effects of population group, sex, and the interaction between population group and sex on the variation among individuals and populations. Discriminant function analyses were used to examine the ability of the two data types to estimate population group, given the significant effect of population group, as well as their ability to estimate sex. While both data types provided low classification rates for population group, both data types provided relatively high classification rates for sex, ranging from 83.8% to 100% accuracy. This study determined that estimating sex from the greater sciatic notch is not only possible, but reliable when using either notch dimension or notch shape data. The use of notch dimension data is the more practical of the two methods, but the reliability of the method is supported by the high classification rates of the notch shape data. Forensic anthropology and bioarchaeology are equally benefited from this new method of estimating sex from the greater sciatic notch of unidentified skeletal remains.

CHAPTER I

Introduction

The overarching goal in forensic anthropology is the identification of skeletal remains. Estimating sex from skeletal remains is a key step in the identification process in both forensic and bioarchaeological contexts. In fact, it is often the first component of the biological profile to be assessed because elements like age, stature, and sometimes ancestry are dependent on the estimation of sex (Scheuer 2002). Further, if an estimation of sex is incorrect, a correct identification is highly unlikely, given the fact that investigators will be looking in the wrong half of the population. Given its importance to developing the biological profile, forensic anthropologists are constantly working to produce methods of sex estimation that are as accurate as possible (Blackmun 1993; Grivas and Komar 2008; Decker et al. 2011).

There are several regions of the skeleton that can be utilized to estimate sex, including the cranium (Walker 2008) and long bones (Jantz and Moore-Jansen 1988; Spradley and Jantz 2011). However, it is generally accepted that the innominate bone displays the greatest degree of sexual dimorphism in humans, making it the ideal bone for sex estimation (Phenice 1969; Meindl et al. 1985; Bruzek 2002; Kjellström 2004). The high degree of sexual dimorphism in the shape and size of the pelvis is the result of females giving birth to large-brained infants, under the constraints of the human trait of bipedal organization to the pelvis and lower limbs (Krogman 1951; Washburn 1960; Rosenberg 1992; Hager 1996; Rosenberg and Trevathan 1996; Wittman and Wall 2007; Walsh 2008; Franciscus 2009; Trevathan 2011; Wells et al. 2012).

Many methods exist to examine different traits of the pelvis to estimate sex. Such methods include studying the morphology of the pubic bone (Phenice 1969), an index of measurements from the ischiopubic region (Washburn 1948), shape and dimensions of the greater sciatic notch (Acsádi and Nemeskéri 1970; Buikstra and Ubelaker 1994; Hager 1996), the presence or absence of a preauricular sulcus (Kelley 1979a), or a combination of multiple traits of the pelvis (Rogers and Saunders 1994; Bruzek 2002; Listi and Bassett 2006). The osteological compromise of human females between upright locomotion and birthing large-brained infants is visible in the greater size and shape of the pelvic inlet (Hager 1996; Kurki 2007). The shape and size of the greater sciatic notch is directly correlated with the size of the pelvic inlet (Hager 1996; Bytheway and Ross 2010). Based on this correlation, multiple studies have demonstrated that the greater sciatic notch is highly accurate for estimating sex when used alone (Letterman 1941; Hager 1996; Walker 2005; Pretorius et al. 2006; Bytheway and Ross 2010).

Not only is the greater sciatic notch extremely useful for estimating sex, it is also a region of the innominate bone that is more likely to avoid significant damage over longer periods of time, retaining its usefulness in sex estimation. In archaeological excavations, and some forensic cases, skeletons are subject to post-mortem damage and other taphonomic processes that may greatly affect regions often utilized in sex estimation (Kjellström 2004). In both forensic and archaeological contexts, other features on the innominate are often missing, due to damage or taphonomic factors (Bytheway and Ross 2010), which may hinder the ability to estimate sex from visual assessment of the os coxa. For instance, preservation of the pubic region in archaeological samples is typically no greater than 30% (Waldron 1987).

Bone density has a major influence on the survival of a bone over time through inhumation and excavation (Galloway et al. 1997). Due to the particularly dense bone in the surrounding area of the innominate, specifically the ischial tuberosity and the auricular surface of the ilium, the greater sciatic notch is also rather dense and structurally durable (Taylor and DiBennardo 1984). Further, the region of the innominate containing the greater sciatic notch has been shown to have higher survivability rates than more fragile, and less dense, portions of the pelvis, in forensic and archaeological contexts (Kelley 1979b; Stojanowski et al. 2002). The high survivability rate, in combination with the direct correlation to pelvic sexual dimorphism in size and shape, suggest that the greater sciatic notch is an ideal bone feature to use when estimating sex.

Many of the traditional methods of estimating sex, including visual or metric assessment of either the entire pelvis or a specific pelvic region, have proved to be inconsistent across populations and researchers (Phenice 1969; Lovell 1989; MacLaughlin and Bruce 1990). The advances of modern technology like three-dimensional scanning and coordinate mapping have resulted in the development of geometric morphometric (GM) analysis, which analyzes the geometric properties of shape to compare morphological differences in individuals and groups. The purpose of this research is to analyze the sciatic notch using two different GM approaches, in an attempt to improve sex estimation.

Traditional Methods of Sex Estimation

Traditional methods of sex estimation include visual observation and metric analysis of skeletal traits. Visual methods of sex estimation that use the human bony pelvis have been widely used in biological anthropology, but have also produced controversial classification results. In the pelvis, these methods examine the variation in shape, or morphology, of various pelvic features between individuals and groups, as determined solely through visual assessment (Bytheway and Ross 2010). These methods are primarily based on the subjective observations of the researcher, which can vary greatly depending on the particular researcher or the observer's level of experience (Bruzek 2002). This variation in observer interpretation is only one factor that produces inconsistent classification results from some of the common visual sex estimation methods that use any portion of the pelvic bone.

Despite the durability of the region of the innominate containing the sciatic notch (Taylor and DiBennardo 1984), many visual methods utilize various regions of the pelvis. This is especially true of the pubic region because it has proven highly efficient in discriminating sex (Walker 2005). Perhaps the most commonly used visual method of sex estimation from the pelvis is Phenice's (1969) examination of three traits of the pubic bone (os pubis). The method uses a simple presence/absence dichotomous scoring system to look at the ventral arc, subpubic concavity, and medial aspect of the ischiopubic ramus on the pubic bone. The original study found that the method could accurately estimate sex over 95% of the time. A critique of this method presented the frequencies of observing the Phenice (1969) traits in a different skeletal sample and found that the technique used "well-defined distinctions and reliable sex evaluations" (Kelley 1978, page 122). However, a later test of the Phenice (1969) technique, performed by Lovell (1989), accuracy rates averaged close to 83% across varying levels of researcher experience. Further tests of the Phenice (1969) method yielded even less favorable results, ranging from 59% to 83% accuracy between three different populations (MacLaughlin and Bruce 1990).

When used in combination with statistical techniques, visual methods may produce slightly more accurate classification results. For instance, when combined with statistical methods, the use of Phenice's (1969) visual method by experienced users generated accuracies nearing 95% (Klales et al. 2012). However, the only published validation study at this time of the method presented by Klales and colleagues is a poster abstract (Kenyhercz 2012). Given the broad range of classification rates when examining the os pubis alone, the use of the Phenice (1969) or Klales et al. (2012) methods alone is not sufficiently reliable. However, incorporation of the sciatic notch would improve classification rates over the use of the pubic region alone.

Another commonly referenced method of visual assessment of sex considers multiple features of the entire innominate bone (Bruzek 2002). In an attempt to address issues of subjectivity in other methods, Bruzek examined sex differences in the morphology of five pelvic features: aspects of the preauricular surface, aspects of the greater sciatic notch, the form of the composite arch, the morphology of the inferior pelvis, and ischiopubic proportions. The characteristics of these features were described as having male, female, or intermediate forms of expression, and the total numbers of female or male traits were compared to estimate sex (Bruzek 2002). This method was applied to two population samples, one French and one Portuguese, of known sex and accurately estimated sex 95% of the time. His claim was that his method would reduce subjectivity of the process by simplifying the interpretation and clarifying the classification criteria. However, in later tests of Bruzek's (2002) technique, classification accuracy rates were discovered to be closer to 89% (Listi and Bassett 2006). The inconsistent classification rates with this visual method do not provide a reliable enough method for forensic anthropology.

The most common method of sex estimation using only the greater sciatic notch is the scoring system of notch shape, originally presented by Acsádi and Nemeskéri (1970). Typically cited as a “standard” method of visual sex assessment (Buikstra and Ubelaker 1994), the system is used frequently by anthropology students and professionals (Walker 2005). The method utilizes a 5-score scale of notch shapes, with scores of 1 considered “highly female” and scores of 5 considered “highly male” (Acsádi and Nemeskéri 1970; Buikstra and Ubelaker 1994; Walker 2005). In a study of this method, Walker (2005) found that there was greater variation in male notch shapes than in female notch shapes, with the greatest amount of overlap in notches with a score of 2. The greater variation in male notch shapes is likely due to the greater restriction on female morphology to allow for parturition of large-brained infants (Walker 2005). The overlap of males and females with a notch score of 2 is counterintuitive to the 5-point scale, which would seem to have the greatest degree of overlap in the median score of 3. Walker asserts that the method produces similar results to some metric approaches, but this scoring system is simpler and can be used on fragmentary specimens. However, Walker also points out that more empirical studies should be conducted using collections with known sex to help eliminate sex estimation biases that are frequently introduced into reconstructions of paleodemography, but no such studies have been published.

Metric methods, which analyze differences in linear measurements correlated with morphology, have been presented as highly objective and easily repeatable methods of estimating sex. Unfortunately, the results of these methods in multiple studies have been nearly as inconsistent as the visual techniques. Some common metric analyses of the pelvis have used either an index of measurements of the ischiopubic ramus (Washburn 1948), or discriminant functions of multiple pelvic measurements (Patriquin et al. 2005; Steyn and İşcan 2008).

A common approach to metric assessment of sex is to use a discriminant function from multiple measurements of the pelvis. With accuracies ranging from 79.7-95.5% in a Greek population (Steyn and İşcan 2008) to 94-95.5% in two South African populations (Patriquin et al. 2005), discriminant functions based on metric measurements do not seem to provide more consistent or accurate results than non-metric, visual methods. Another study tested the reliability of metric methods applied to virtually reconstructed CT scans and found that accuracy could consistently be 100% using a four-variable formula (Decker et al. 2011). Decker and colleagues then compared the results of their CT method to the classification results of the most commonly employed metric method in the discriminant program FORDISC 3.0, which only estimated sex correctly for 86% of the specimens.

Metric methods have also been applied to the greater sciatic notch region alone (Letterman 1941; Taylor and DiBennardo 1984; Takahashi 2006). These methods are primarily based on indices of measurements like width, depth, and angles of the notch (Singh and Potturi 1978). Takahashi (2006) calculated indices of the geometric curvature, depth-to-width ratio, proportions of width, and angles of the sciatic notches of a Japanese skeletal collection of known sex. Out of ten variables, Takahashi found that the posterior angle was the best discriminator of sex with 91% accuracy, and he proposed an analysis of geometric curvature representing localized shape, which correctly estimated sex 88% of the time. Although the author suggests that the analysis of maximum notch curvature may be useful in specimens with postmortem damage, the classification accuracies are actually better in the simpler analysis of notch angle. This incongruity requires a closer examination of the various components of notch shape that contribute to accurate sex estimations.

The discrepancy between the accuracy rates found in these common studies and their validation tests is likely related to various factors. One likely factor is the age of the skeletal samples, which may have resulted in varying accuracies in studies that used the same sex estimation method. For instance, Phenice (1969) developed his method based on a sample from the Terry Collection, which consists of individuals born in the late 19th – early 20th centuries, while Kelley (1978) used samples of unknown skeletons from prehistoric collections and Lovell (1989) used a sample of modern medical school cadavers. Lovell (1989) did note that changes to the pubis resulting from increased age of an individual could decrease the utility of any of the Phenice (1969) traits. Secondly, the application of the method being tested to demographically different skeletal samples could cause variation in performance. For instance, Phenice (1969) used a selection of specimens from the Terry Collection, which is made up of samples of White and Black individuals. However, Lovell's (1989) test of Phenice (1969) used individuals that were presumed to be White, and Kelley (1978) used prehistoric Native American collections of unknown sex. The use of these methods on population groups other than those used to create the methods is problematic because it disregards human variation, specifically variation created by different population histories leading to differing genetic traits.

Many of the traditional methods, with their multitude of inconsistencies, have been broadly applied to various population groups, and yet tested on very few population samples with known sex. Like the Phenice (1969) method, many methods have been consistently tested only on documented collections of American and South African Whites and Blacks, but there has been little to no research done on the application of these methods to samples of Hispanic individuals. The application of methods of sex estimation to different population groups is based on the principle that each group has a unique population history that has led to variation in the skeleton (Letterman 1941; and MacLaughlin and Bruce 1985; Steyn and İşcan 2008; Steyn and Patriquin 2009). Although Steyn and Patriquin (2009) questioned the necessity, many researchers agree that population-specific formulae are required to account for the varying degrees of sexual dimorphism in different populations (MacLaughlin and Bruce 1985; Rogers and Saunders 1994; Bruzek 2002; Steyn et al. 2004; Patriquin et al. 2005; Steyn and İşcan 2008).

Traditional methods of sex estimation are severely lacking in both consistent classification results and a detailed examination of method utility across populations (Bruzek 2002; Bytheway and Ross 2010). Given these flaws in traditional visual and metric sex estimation methods, an improved approach is required. Geometric morphometric methods provide an improvement over traditional techniques by capturing and analyzing the complex relationships among structures and their shapes (Slice 2005).

Geometric Morphometrics

Shape constitutes the geometric features of an object that do not change relative to location, size, or orientation (Bookstein 1997; Slice 2005; Slice 2007), and morphometrics is the study of size and shape variation among individuals or populations (Rolf and Marcus 1993; Slice 2007). Traditional morphometric analyses involved applying multivariate statistics to measurements of distance, angle, or distance ratios, as a way to study the variation in size and shape among specimens (Letterman 1941; Washburn 1948; Takahashi 2006; Slice 2007). Geometric morphometrics encompasses multiple techniques that create a quantifiable way to analyze shape differences among specimens. Geometric morphometrics uses two- or three-dimensional Cartesian coordinates collected from landmark or semilandmark points in order to fully capture the spatial arrangement of anatomical points, without creating the impractical number of variables that comes from traditional morphometrics (Rolf and Marcus 1993; Slice 2005; Slice 2007). Where traditional morphometrics looks at size and shape, geometric morphometrics can either remove size from the analysis of shape or analyze the effect of size, as a separate variable, on the variation in shape (Slice 2005; Slice 2007).

Landmarks vary in the quality of information they hold, and are therefore classified into three types (Bookstein 1991; Slice 2005). Type I landmarks are often defined as specific features of bone, being homologous points across forms. Type II landmarks are generally curvature maxima defined in direct reference to a nearby bone feature, but they are not homologous across individuals. Type III landmarks are roughly defined points that demarcate extremities in measurements, related only to distant bone structures. Since Types I and II are defined in reference to specific, local structures, they allow for direct comparison of the relationship between landmarks across individual specimens (Bookstein 1997; Adams et al. 2004; Slice 2005). Semilandmark analysis takes geometric morphometrics even farther by introducing a technique to compare the curves and surfaces between those homologous landmarks on different specimens (Gunz and Mitteroecker 2013).

With the modern technology of three-dimensional coordinate measurement, geometric morphometric methods have been applied to skeletal remains to assist with identification. Geometric morphometrics has gained increasing respect in the fields of forensic science (Zelditch et al. 2012) and biological anthropology (Baab et al. 2012). Several researchers have examined the usability of geometric morphometric analysis in estimating the sex of human skeletal remains (Pretorius et al. 2006; Bytheway and Ross 2010). There have also been several studies using geometric morphometric analysis to estimate sex from the greater sciatic notch (Steyn et al. 2004; Gonzalez et al. 2007; Gonzalez et al. 2009). Gómez-Valdés et al. (2012) compared the accuracy of common visual, metric, and geometric morphometric approaches when estimating sex from the greater sciatic notch and found that the geometric morphometric method was the most accurate, at 95%.

Previous research has shown a high classification accuracy of sex using geometric morphometric analysis of greater sciatic notch dimensions. The analysis used notch dimensions derived from three points defining the width and depth of the notch, and classifications of sex were accurate 96% of the time (Hessey 2012), which is higher than multiple studies of traditional approaches (Phenice 1969; Lovell 1989; Bruzek 2002; Walker 2005; Listi and Bassett 2006; Takahashi 2006). However, the study only examined two population groups, which may not account for enough variation among groups. The previous study also did not test for variation between population groups, which has been shown to be a relevant factor in sex estimation (MacLaughlin and Bruce

1985; Rogers and Saunders 1994; Bruzek 2002; Steyn et al. 2004; Patriquin et al. 2005; Steyn and İşcan 2008). Further, although the results of the previous study were promising, three points defining the notch dimensions may not adequately capture notch morphology and may not account for the greatest amount of variation (Rolf and Marcus 1993). Given that the previous study presents a somewhat incomplete image of geometric morphometric analysis of sciatic notch morphology, a more thorough investigation is warranted. By using semilandmark data, notch shape can be examined in more detail.

Research Questions

The research presented in this paper represents an attempt to answer a set of questions regarding sex estimation from the greater sciatic notch of the pelvis. The purpose of this research is to examine (1) if population differences exist in notch shape or notch dimensions, can either data type be used to estimate population group, and (2) does notch shape or notch dimension data improve sex estimation.

The proposed research will use population groups of American White, American Black, and Central Mexican individuals and determine the reliability of two different geometric morphometric techniques for accurately estimating sex in these populations. Two types of data will be utilized to answer the research questions stated above: (1) three-dimensional coordinates of three defined landmark points from which notch dimensions are derived, and (2) three-dimensional coordinates of continuous semilandmarks collected from the notch outline. Due to the potential for inter-population skeletal variation, standards used to assess sex should be population- and period-specific, when possible (SWGANTH 2010). This requires newly developed methods, such as those presented here, be tested for accuracy in other populations.

CHAPTER II

Materials & Methods

Samples

This study utilizes data from samples of American Blacks, American Whites, and Central Mexicans. Samples of American Blacks and American Whites were collected from the Terry Collection housed by the Smithsonian Institution's National Museum of Natural History in Washington, DC (Hunt and Albanese 2005). The Terry Collection was assembled between 1927 and 1967 from medical school cadaver remains. It is made up of 1,728 specimens of known age, sex, ethnic origin, cause of death, and pathological conditions, representing individuals born between 1822 and 1943. The collection has a demographic distribution of 461 White males, 546 Black males, 323 White females, 392 Black females, 5 Asiatic males, and one individual of unknown origin. In this study, samples taken from the Terry Collection represent American Whites and American Blacks.

The American White sample was also supplemented with data taken from the Texas State Donated Skeletal Collection (TSDSC) at the Forensic Anthropology Center at Texas State University. This collection is made up of individuals who were either living-donors or next-of-kin donations to the longitudinal decomposition research and osteological collection at Texas State University. The collection began in 2008 and currently holds approximately 70 individuals available for study. The collection is constantly being added to, but currently holds around 34 White males, 4 Black males, 3 Hispanic males, 25 White females, and 2 Black females. Ages of the individuals range from roughly 30 to 102 years old. Individuals are typically residents of Texas, but as the collection grows, donations are coming from farther away.

The Central Mexican sample was collected from the Osteological Collection of the Universidad Nacional Autónoma de México (UNAM), at the Physical Anthropology Laboratory, Department of Anatomy, School of Medicine (Gómez-Valdés et al. 2012). Beginning in 1960, the collection was assembled from cadavers used in the School of Medicine at the National University, and specimens continue to be incorporated into the collection. The collection currently holds 230 individuals, with approximately 127 males and 103 females representing a contemporary Mexican Mestizo population from Central Mexico, primarily Mexico City. Individuals were born between 1899 and 1987, and were between the ages of 18 and 92 at the time of death.

The number of specimens used in this study varied based on the analysis (Table 1). Due to previous data collection problems, a portion of the Terry Collection data was identified as outliers and removed from the notch shape analysis. Sample sizes for American Whites were supplemented with specimens from the TSDSC, resulting in the use of 27 males and 34 females from the Terry Collection, and 21 males and 14 females from the TSDSC, in the notch shape analyses. The American Black male sample was unable to be supplemented, due to insufficient specimens in the TSDSC.

All individuals in the samples were between the ages of 37 and 79 at the time of death. Individuals from the Terry Collection were randomly chosen and only excluded from analysis based on missing innominates or extensive damage. Random sampling could not occur in the TSDSC given the limited number of individuals in the collection, but individuals were also only excluded from data collection due to extensive damage to the sciatic notch region of the innominate. Individuals from the UNAM collection were chosen based on adherence to the chosen age range, and random sampling could not occur due to a limited collection size.

Table 1. Number of specimens used in each type of analysis.

Type of Analysis		American Black	American White	Central Mexican	Total
Notch Dimensions	Males	50	72	50	172
	Females	50	65	50	165
	Total	**100**	**137**	**100**	**337**
Notch Shape	Males	25	48	49	122
	Females	41	48	49	138
	Total	**66**	**96**	**98**	**260**

Research Design

For each specimen, innominates were placed within reach of the arm of a Microscribe® 3DX digitizer (Immersion Corp., San Jose, CA), oriented with the postero-lateral surface of the innominate facing up, and stabilized using modeling clay. The digitizer was interfaced to a laptop computer, which recorded the three-dimensional coordinate points (x, y, and z) in millimeters into a Microsoft® Excel (2013) spreadsheet, utilizing the MicroScribe® Utility software (Immersion Corp., San Jose, CA). In the case of fusion of the sacro-iliac joint, an attempt was made to position the greater sciatic notch in the same approximate position used when innominates were separate, but the use of more clay allowed for an adjustment to the angle, or plane, of the notch. Data was collected from both left and right innominates of each individual, but only measurements taken from left innominates were used in the analyses for this research.

Defining Notch Dimensions

Three-dimensional coordinates were collected for three points along the outline of each greater sciatic notch, defining the greatest extent of the notches. Point A was taken at the most anterior projection at the termination of the posterior border of the notch (Davivongs 1963, Patriquin et al. 2005). This point will likely be anterior to the posterior inferior iliac spine and occurs where the bone begins to curve posteriorly away from the notch, which will clarify where to locate this point when the pyramidal projection is not particularly large. It is important to note that this point is not taken from the posterior inferior iliac spine. Further, the presence of a preauricular sulcus should not preclude this point from being taken because the anterior projection of the bone surrounding the sulcus is an inherent part of the notch outline. Since the notch outline is the shape used to assess sex visually, it is important that this is the same shape assessed morphometrically in this study.

Point B is taken at the base of the ischial spine on the anterior border of the notch (Kelley 1979b). It is important to place the point exactly where the spine begins to project posteriorly from the ischium because, in the instance of a broken ischial spine, this point will likely still be able to be found due to the durable bone of the ischium. Point C is the deepest point of the notch, as determined by a pencil held perpendicular to the line A-B (Steyn and İşcan 2008) (Figure 1).

These three points define the corners of a triangle, and the edges and height of that triangle define the width ($\overline{AB}$), and depth ($\overline{C-AB}$), of the notch, as well as the dimensions of the triangle created (Figure 1). Geometric distances were calculated from the 3D coordinate data, providing the measures of the sides of the triangle, and the measures of the angles in the triangle were calculated using basic geometry. To calculate the depth of the notches, Heron's formula (Figure 2.b) was inserted into the formula for

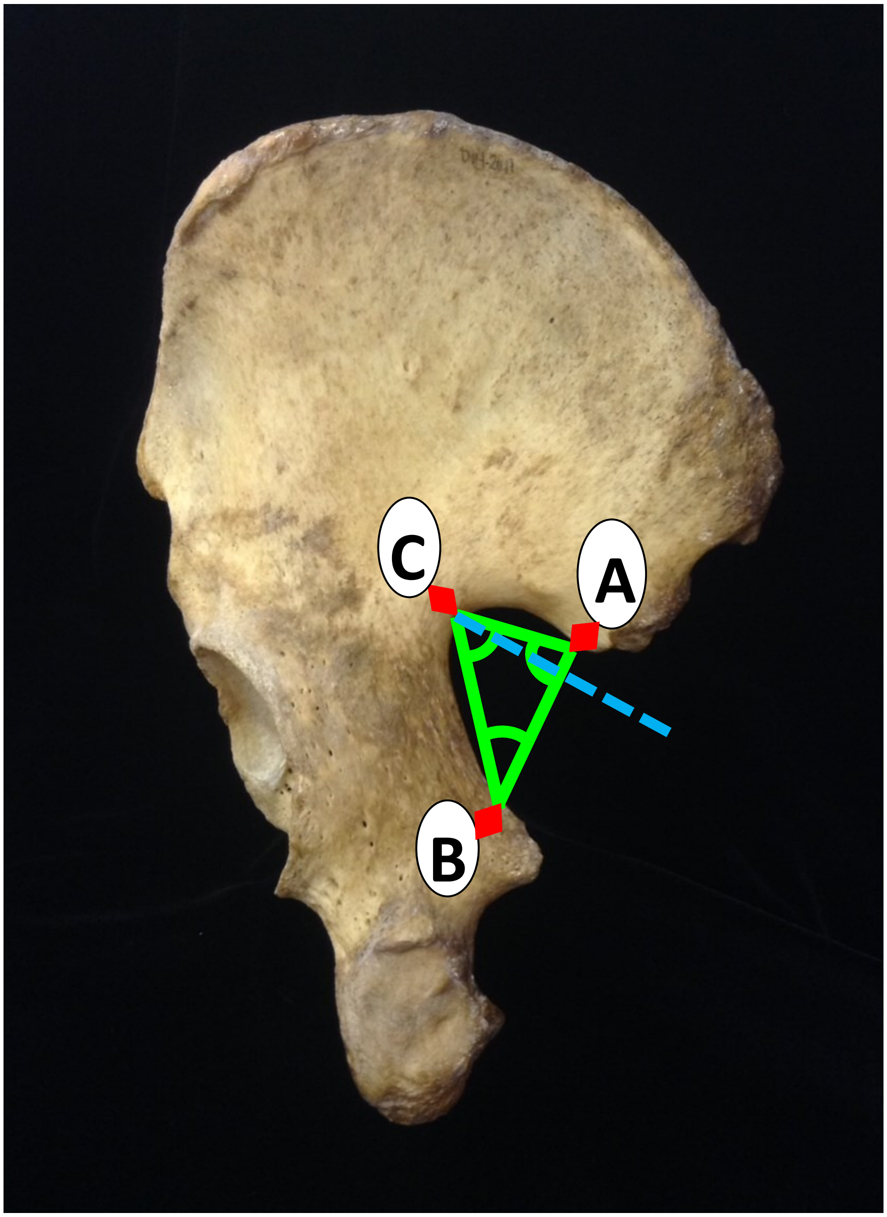

Figure 1. Orientation of the three points of the greater sciatic notch. In alphabetical order: (A) most anterior point on posterior border of notch, (B) ischial spine, and (C) deepest point of the notch. The dashed blue line represents the depth of the notch, while the solid green lines represent the triangle created by the three points.

the area of a triangle (Figure 2.a) that has been rearranged to solve for the height (Figure 2.c). The seven dimensions of the notch, three sides, three angles, and the height of the triangle, were used as variables in the notch dimension analysis.

(A) $$A = \frac{1}{2} b * h$$

(B) $$A = \left(\sqrt{s(s-a)(s-b)(s-c)}\right)$$

$$s = \frac{a+b+c}{2}$$

(C) $$h = \frac{2}{c}\left(\sqrt{s(s-a)(s-b)(s-c)}\right)$$

Figure 2. **Formulas used to calculate notch dimensions.** (A) Area of a triangle, (B) Heron's formula, with the value of *s*, and (C) the complete formula used to determine the depth of the sciatic notches.

Defining Notch Shape

Three-dimensional coordinates were also collected from each individual to produce contours of each notch. To collect this data, the Microscribe was used to collect semilandmark coordinates along the outline of the notch. The digitizing arm was slowly moved from point A to point B (described above), collecting coordinate points at every 0.5mm along the curve. These semilandmarks provide a complete representation of the size and shape of each notch (Figure 3).

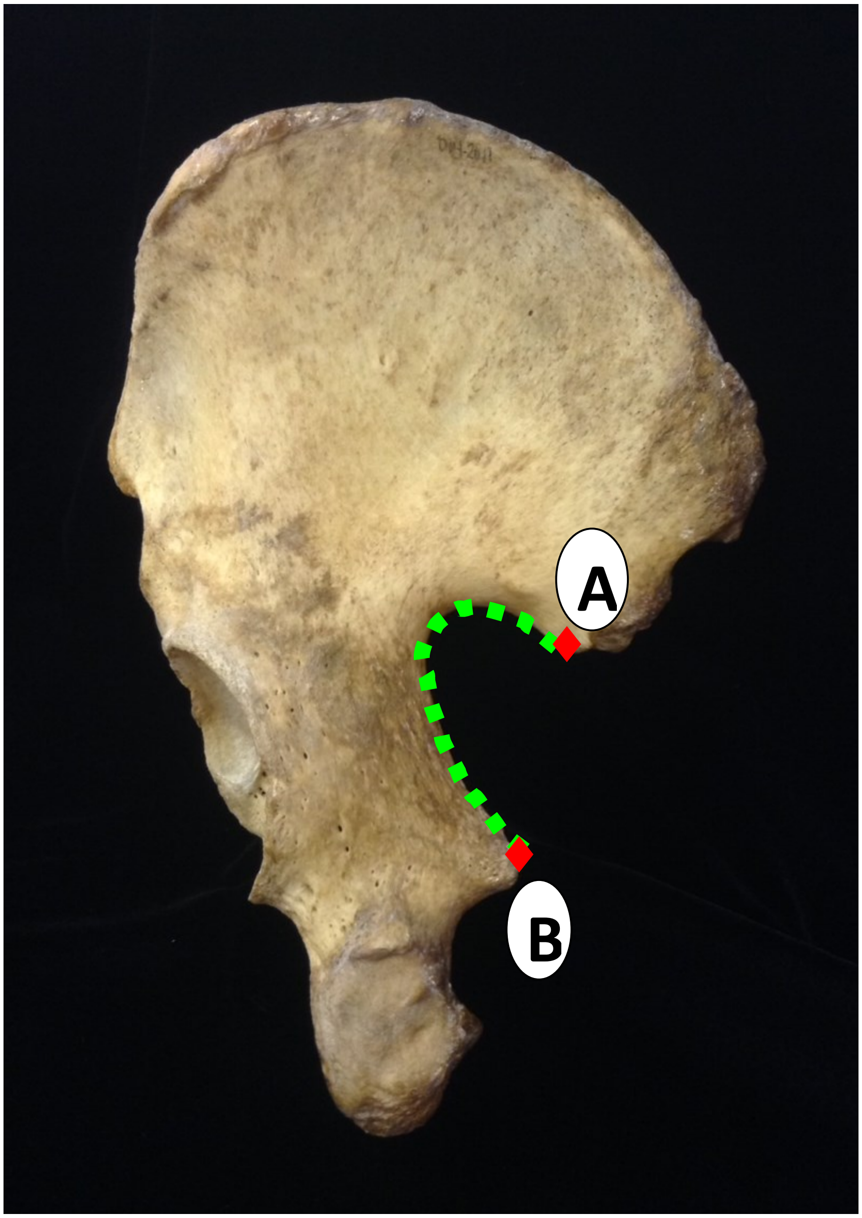

Figure 3. Illustration of digitizer path to collect notch shape data. The path went from point A to point B, along the dashed green line.

Before any statistical analyses were performed on the 3D coordinates, the raw data underwent a resampling process to reduce and standardize the number of semilandmark points used in subsequent analyses (Gunz and Mitteroecker, 2013). This step was completed using *resample.exe* (Raaum, 2006) a computer program that measures the length of the curve described by the three-dimensional data, divides that length into the desired number of points, and calculates the coordinates of the new semilandmark points using weighted linear interpolation. For this research, it was determined that 50 points would appropriately describe the shapes of the sciatic notches measured. This resampled data was then input into the geometric morphometric computer program *Morpheus et al.* (Slice 2013), which transformed the data by a generalized procrustes analysis to remove the effects of size, orientation, and position.

Statistical Analyses

Among Group Variation

Notch Dimensions

Using the statistical program SPSS Statistics 21 (IBM), a multivariate analysis of variance (MANOVA) was used to examine differences in sex, population group, and the interaction between sex and population group for notch dimension data. Should the MANOVA return significant results, two three-group stepwise discriminant function analyses (DFAs) will be performed to estimate population group, when sex is known. One analysis will use males only and the other will use females only to estimate population group.

Notch Shape

Using the SAS System for Windows version 9.1.3 (SAS Institute), a principal components analysis (PCA) was performed on the procrustes-aligned coordinates generated in *Morpheus et al.* in order to reduce the number of variables for subsequent analyses and concentrate the variation between individuals. The analysis produced principal components (PC), distinguished based on the amount of variance explained. A stepwise DFA was performed to determine which PCs explained the greatest amount of variance between individuals. This method determined that principal components 2 and 6 explained the most variance between individuals and the subsequent analyses for notch shape utilized data only for those two PCs. A MANOVA was performed using the scores from PCs 2 and 6, examining differences in sex, population group, and the interaction between sex and population group for notch shape data. If the MANOVA returns significant results for each comparison, two three-group DFAs will be performed to estimate population group, given sex. One DFA will use only males and the other will use only females, but both DFAs will use the scores from PCs 2 and 6.

Estimating Sex

Notch Dimensions

Following significant results of the MANOVA comparison of population groups, a stepwise DFA for sex will be performed on each population group separately, as well as a third stepwise DFA for sex using all population groups. The stepwise procedure will select the dimension variables that best separate the sexes and produce classification functions for estimating sex. Classification accuracy rates will be provided from a cross-validation test of the classification functions.

Notch Shape

If the MANOVA using PCs 2 and 6 finds significant differences between population groups, three stepwise DFAs for sex will be performed on those PC scores, one for each population group, and one using all population groups. A cross-validation test will provide classification accuracy rates for each population group.

Review Board Approval

Due to the nature of my study sample, IRB and IACUC approval were not necessary for completing this research. Data collected from human skeletal remains only requires the permission of the collection manager.

CHAPTER III

Results

Among Group Variation

Notch Dimensions

The multivariate analysis of variance (MANOVA) run on the dimensional data examined differences in sex, population group, and the interaction between sex and population group. The results of the MANOVA showed a statistically significant difference in all comparisons (Table 2). Given the significant difference among population groups, a discriminant function analysis (DFA) for population group, by sex, is warranted using notch dimension data.

Two three-group DFA for population group were performed on males and females, separately. The DFA for males had relatively low classification rates for population group. American Black males were correctly classified 64.7% of the time, while American White and Central Mexican males were correctly classified 55.6% and 58%, respectively. Overall, the DFA estimating population group of males had a cross-validated classification rate of 59%.

The DFA for population group was performed on females and had highly variable classification rates. Central Mexican females had the poorest classification rate of all the population groups, with a rate of 30%. In comparison, American Black females had a classification rate of 68% and American White females correctly classified for population group 60.9% of the time. The overall cross-validated population group classification rate for females was 53.7%.

Both DFAs produced statistically significant classification rates (p<0.001). Unfortunately, males were only correctly classified by population group an average of 59% of the time and females were only correctly classified 53.7% of the cross-validated grouped cases. The DFA for population group results are summarized in Table 3.

Notch Shape

The principal components analysis (PCA) of the procrustes shape data produced 150 principal components. The stepwise DFA extracted PCs 2 and 6 as the components that contributed the most to among group variation. These PCs accounted for nearly 53.5% of the variance in all the variables. The multivariate analysis of variance (MANOVA) run on the scores from PCs 2 and 6 examined differences in sex, population group, and the interaction between sex and population group. The results of all three comparisons of the MANOVA were statistically significant with a p-value less than 0.0001 (Table 2). The significant differences found among population groups warrants testing the ability to estimate population group from notch shape data, when sex is known.

Given the significant differences between the notch shapes of population groups, two DFAs were performed to see if classification of ancestry was possible using notch shape data when sex is known (Table 3). The first DFA for population used notch shape data from only males and produced varying classification rates. American Black males had the highest classification rate, being correctly assigned to their population group 92% of the time. American White males had the lowest classification rate, with 70.8% accuracy, while Central Mexican males were correctly classified 81.6% of the time. Overall, the DFA classified 79.5% of males into the correct population group.

The second DFA for population group, performed on females, produced highly variable classification rates. Central Mexican females had the highest accuracy for classifying population group, with 91.8% of cases correctly assigned. Females were correctly assigned to the American White population group 83.3% of the time, and American Black females were correctly classified in 56.1% of cases. The average rate of classifying females into the correct population group is 78.3%.

Table 2. MANOVA results for the effect of population group, sex, and an interaction between population group and sex for American Blacks, American Whites, and Central Mexicans.

	Population Group		**Sex**		**Population Group*Sex**	
	F-value	p > F	F-value	p > F	F-value	p > F
Dimension	.644	< 0.0001	.425	< 0.0001	.855	< 0.0001
Shape	.0008	< 0.0001	.0043	< 0.0001	.0056	<0.0001

Table 3. Cross-validated classification results of males and females for population groups.

		American Black		**American White**		**Central Mexican**	
	Sex	n	%	n	%	n	%
Notch Dimensions	Females	34	68	39	60.9	15	30
	Males	33	64.7	40	55.6	29	58
Notch Shape	Females	23	56.1	40	83.3	45	91.8
	Males	23	92	34	70.8	40	81.6

Sex Estimation

Notch Dimensions

The difference among population groups, shown by the results of the MANOVA of notch dimension data, suggested performing separate DFAs on each population group to estimate sex. A fourth DFA for sex was performed using all population groups, to account for realistic scenarios in forensic anthropology. The resulting discriminant functions are listed in Table 4. The DFAs produced relatively high cross-validated classification rates for sex (83.8-93%), across all three populations, and accounted for statistically significant differences between the sexes (Table 5).

In the first DFA, performed on American Blacks, males had a classification rate of 80.4% and females had a classification rate 88%. The sex of American Black individuals was correctly classified an average of 84.2% of the time. In the second DFA, American White individuals were correctly classified as male or female an average of 83.8% of the time. American White males were correctly classified 81.9% of the time while females had a classification rate of 85.9%. The third DFA was performed on Central Mexicans, where males had the highest classification rate of all the groups, with correct classifications 98% of the time. Mexican females were correctly classified at a rate of 88%. Central Mexicans had an average classification rate of 93%. The final DFA was performed using all three population groups and correctly classified males 88.4% of the time, and females 89% of the time. The average classification rate for sex, regardless of population group was 88.7%.

Table 4. Discriminant functions for classifying sex using notch dimensions.

Population group	Function	Cross-validated Classification Rate
American Whites	F(x) = 0.144 (DEPTH) + 0.153 (Angle A) – 12.128	83.8%
American Blacks	F(x) = 0.153 (Dist AC) + 0.173 (Angle A) – 13.504	84.2%
Central Mexicans	F(x) = 0.756 (DEPTH) – 0.508 (Dist AC) – 3.248	93%
All Populations	F(x) = 0.122 (DEPTH) + 0.139 (Angle A) – 10.698	88.7%

Notch Shape

Given the significant difference among populations, found in the MANOVA of notch shape data, each population group was analyzed separately for the ability to discriminate between males and females. Using only the PCs extracted during the stepwise DFA procedure, PCs 2 and 6, one DFA for sex were performed for each population group, and one DFA for sex was performed regardless of population group. The classification results of these DFAs are listed in Table 5.

The first DFA was performed using American Whites and classified for sex an average of 95.8% of cross-validated individuals correctly. American White males had a classification rate of 97.9%, while American White females had a classification rate of 93.8%. The second DFA, performed on American Blacks, had an average cross-validated classification rate of 82.7% for males and females, overall. American Black males had a classification rate of 80%, while American Black females classified correctly 85.4% of the time. In the third DFA, Central Mexican individuals correctly classified as male or female an average of 100% of the time. Mexican males and females both had 100% classification rates. The final DFA for sex, performed using all population groups, had an average cross-validated classification rate of 91.5%. Males were correctly classified 94.3% of the time and females were correctly classified 89.1% of the time.

Table 5. Cross-validated classification results of DFAs for sex.

	Population group	Female %	Male %	Overall %	Wilks' lambda / Chi-Square	p-value
Notch Dimension	American Blacks	88	80.4	84.2	.449	< 0.0001
	American Whites	85.9	81.9	83.8	.475	< 0.0001
	Central Mexicans	88	98	93	.350	< 0.0001
	All Populations	89	88.4	88.7	.454	< 0.0001
Notch Shape	American Blacks	85.4	80	82.7	17.18	0.0007
	American Whites	93.75	97.9	95.8	13.79	0.0032
	Central Mexicans	100	100	100	62.05	< 0.0001
	All Populations	89.1	94.3	91.5	196.6	< 0.0001

CHAPTER IV

Discussion and Conclusion

The pelvis is generally accepted as the most sexually dimorphic region of the human skeleton and the greater sciatic notch is one feature that has been consistently used as a reliable source for sex estimation (Letterman 1941; Phenice 1969; Meindl et al. 1985; Hager 1996; Bruzek 2002; Kjellström 2004; Walker 2005; Pretorius et al. 2006). While the use of visual or metric methods have been abundantly common in sex estimation by forensic anthropologists, the use of methods like geometric morphometric analysis allows for not only an expanded toolkit for the forensic discipline, but also for improvement over traditional methods (Slice 2005). Three-dimensional coordinate data can be utilized in many different types of analyses, including simple geometric measurement or the more complex geometric morphometric analysis.

It is established that geometric morphometric methods provide increased reliability in estimating sex from the pelvis (Steyn et al. 2004; Gonzalez et al. 2007; Gonzalez et al. 2009; Gómez-Valdés et al. 2012). Using the greater sciatic notch, both geometric dimensions and shape analysis have been applied as sex estimation techniques (Steyn et al. 2004; Gonzalez et al. 2007; Gonzalez et al. 2009; Gómez-Valdés et al. 2012). In the current research, the two different approaches to geometric morphometric sex estimation of the sciatic notch were examined for (1) their ability to distinguish among population groups and (2) their reliability in estimating sex. The two methods were compared to see which provides the most accurate method of distinguishing population group and sex.

Among Group Variation

Notch Dimensions

The multivariate analysis of variance (MANOVA) run on the dimensional data showed a statistically significant difference in sex, population group, and the interaction between sex and population group. The significant difference between population groups suggests it might be possible to use notch dimensions for estimating population group. Therefore, a discriminant function analysis (DFA) for population group was performed for each sex. However, the DFA results for discriminating among population groups provided only 59% and 53.7% average cross-validated classification rates for males and females, respectively. Based on random assignment, distinguishing among three population groups should have a 33.3% probability of estimating correctly, and although the DFA results show a higher rate of correct classifications, the rates are not high enough to be applied practically. These results indicate that notch dimensions are not reliable for estimating population group.

The differences in notch dimensions among population groups could be the result of different population histories contributing to variation in genetic structure (Lisker et al. 1990; Chakraborty et al. 1992; Parra et al. 2001; Ross et al. 2004). American Whites have a closer genetic relationship with Europeans than the other two populations, while American Blacks hold a stronger relationship to Africans, and Mexican Mestizos have a stronger genetic relationship to Native Americans (Lisker et al. 1990; Chakraborty et al. 1992; Ross et al. 2004; Spradley et al. 2008). However, these population differences in notch morphology are not described in the literature, and the classification results for population group indicate that sexual dimorphism is fairly consistent across populations.

Despite the statistical evidence for a significant difference among population groups, as well as the significant effect of the interaction between population and sex, the present study suggests the differences are not large enough to classify group based on notch dimensions.

Notch Shape

The MANOVA performed on principal components 2 and 6, from the PCA on the procrustes-superimposed shape data, also revealed statistically significant differences ($p<0.0001$) in notch shape for sex, population group, and the interaction between sex and population group. Again, the significant difference among population groups is expected, as it follows the premise of different population histories leading to genetic variation among groups (Lisker et al. 1990; Chakraborty et al. 1992; Parra et al. 2001; Ross et al. 2004). The difference between population groups was investigated further by performing two DFAs for population on males and females, separately, also using values from PCs 2 and 6.

The DFAs provided overall cross-validated classification rates of 79.5% and 78.3% for males and females, respectively ($p<0.001$). These classification rates indicate a population-specific pattern to notch shape that would not allow for the use of discriminant functions to classify population affinity consistently. This simultaneously enhances information on the influence of population on morphological variation in the sciatic notch, and follows the suggestion for best practice by SWGANTH (2010).

Sex Estimation

The study by Steyn and Patriquin (2009) determined that population-specific discriminant functions for sex were not necessary with White South African, Black South

African, and Greek populations. However, the significant differences found among populations examined in the current study suggest creating separate discriminant functions for each population to estimate sex. Given that the sciatic notch is accepted as having a great deal of sexual dimorphism (Phenice 1969; Meindl et al. 1985; Bruzek 2002; Kjellström 2004), it is also no surprise that the geometric morphometric analysis revealed a statistically significant difference between males and females for notch shape.

Notch Dimensions

Sex estimation from sciatic notch dimensions provides more accurate classification results than those for estimating population group. A DFA was performed on each population group separately and once using all population groups to estimate sex. With average cross-validated sex classification rates between 83.8% and 93% accuracy, this method provides very similar accuracy rates to the corrected accuracies of most of the commonly used methods (Phenice 1969; Lovell 1989; Bruzek 2002; Listi and Bassett 2006). In a practical application, it is encouraging to find that, without knowing population it is still possible to correctly estimate sex in 88.7% of cases, using notch dimensions. Since the estimation of sex is often made before the population group is known or estimated if the pelvis is present, this study shows it is still possible to make an estimation of sex.

The geometric dimensions extracted from the DFAs for notch dimension revolved primarily around the posterior border of the sciatic notch; notch depth, angle A, and the distance between points A and C were the most highly indicative of sex. The size of this portion of the notch has been correlated with the overall size of the pelvic outlet (Genovés 1959; Hager 1996). In males, the posterior border of the notch is typically shortened in relation to the anterior portion, which contributes to the expected narrow notch width (Genovés 1959). The female notch typically displays a longer posterior border than the anterior portion, which contributes to a wider notch and a taller innominate.

Notch Shape

The significant difference between the sexes found in the MANOVA of notch shape data is to be expected, given that sexual dimorphism in the pelvis is an accepted trait, but the statistically significant difference between population groups is most important because it warrants running separate DFAs for each population group. The cross-validated classification results from the population-specific DFAs for sex showed a great deal of variation in accuracy across populations, but had relatively high accuracy rates. With classification rates of 95.8%, 82.7%, and 100%, it seems that notch shape is a useful tool in estimating sex for American Whites, American Blacks, and Central Mexicans, respectively.

Considerations

As explained earlier, a portion of the geometric morphometric data collected in 2011 was determined to be of poor quality and removed from the geometric morphometric analyses. The supplementation of specimen measurements from the Donated Collection at the Forensic Anthropology Center at Texas State University allowed for sample size of White individuals to be returned to almost equal. Unfortunately, the TSDSC collection did not hold enough American Black individuals at the time to supplement sample sizes from that population group, so no new data was collected to replace removed Black males or females from the Terry Collection data.

The difference in population age between the samples could have affected the results of the study. Since the Hispanic population will likely be modern individuals, there might be a question about comparing the new data with the data collected from the Terry Collection (Smithsonian), where individuals were from the early 20th century. Further, with the notch shape analyses, combining the American Whites from the Terry Collection with the TSDSC sample, given the difference in the ages of each collection, may have contributed to some minor confusion in the data. Unfortunately, the nature of skeletal research is to utilize skeletal samples that are available for study, despite small temporal differences in the samples. The ideal study would use a modern sample(s) to reexamine the differences between American White and Black populations, and only one pilot study has indicated that there has been significant secular change in the pelvis in the last 90 years (Klales 2012).

Future Research

Although the results of the current research are promising, several topics can be studied to broaden knowledge on sciatic notch sex estimation. For instance, the current study only examined sex differences using the left sciatic notch. Given the variation in notch shape observed during data collection between the left and right notches of a single individual, future research might examine the significance of asymmetry in sex estimation. Similarly, a preliminary result of the 2012 study by Hessey showed an increase in the classification accuracies when using the left innominate alone versus using both sides together, indicating it to be less important to have both os coxae when estimating sex. However, a more complete analysis of this difference would benefit from the inclusion of the Mexican sample used in the current study as well as from the application of the second geometric morphometric approach using notch shape.

Given the successful classification results of the discriminant functions for shape data, one avenue of further research would be to compare the average notch shape of each sample to the shape categories commonly used for visual estimation of sex (Buikstra and Ubelaker 1994). An analysis of the range of variation in greater sciatic notch shape, and a comparison to the shape categories drawn in *Standards for Data Collection from Human Skeletal Remains* (Buikstra and Ubelaker 1994) would provide an understanding of the correlation between the coordinate method and the classic visual method.

The significant difference found in the interaction between sex and population group for both the notch dimension and notch shape MANOVAs is a particularly interesting result. This finding indicates that each population group displays varying levels of sexual dimorphism, and the differences are statistically significant. This result is contrary to the work of Figueroa-Soto (2012), who examined the sexual dimorphism in long bone measurements across multiple populations. The author found no significant difference in the interaction between population group and sex, meaning sexual dimorphism in long bone measurements did not vary significantly among populations (Figueroa-Soto 2012). The results found in the current study are also contrary to the accepted notion that female pelvic morphology, even more-so than males, is extremely limited in its morphological variability due to the constraints of birthing infants (Meindl et al. 1985; Bruzek 2002). Environmental stress has been demonstrated to influence sexual dimorphism in long bones and stature (Gray and Wolfe 1980; Charisi et al. 2011).

Perhaps a future area of research could examine the possible environmental differences in populations that lead to varying levels of sexual dimorphism in pelvic morphology.

Conclusions

The results of this research concur with the relevant literature, in that the greater sciatic notch provides relatively high accuracy rates in estimating sex. Testing the accuracy of using only left notches is an attempt to realize the potential for the method when incomplete skeletal remains are present, for instance in archaeological contexts. Although the accuracy in sex classification based on notch dimensions does not greatly exceed the range of accuracy when using other methods using the pelvis, it remains a plausible method for use if, perhaps, the sciatic notch region is the only pelvic feature available for analysis. With geometric morphometric analysis of notch shape, classification rates for sex are slightly higher than other traditional methods, making it an even more reliable method for sex estimation. Although the practicality of using the notch shape method is questionable, given the complexity of the analyses involved, the high classification accuracies indicate that more weight can be placed on the notch dimension classification results because the notch dimensions are a more simplified form of the notch shape data.

The significant differences among population groups, found in the MANOVA results, warranted the use of separate discriminant function analyses for sex for each group, in both types of data. The geometric morphometric analysis of notch dimensions did not produce a reliable discriminant function for estimating population group, but the analysis of notch shape was able to classify population group to a relatively reliable degree.

The results of this study can be applied in a forensic context to assist investigators in either estimating sex from the greater sciatic notch whether population group is known or not. Fragmentary skeletal remains can be found in forensic contexts, so the methods presented in this study provide a sex estimation technique from a small portion of bone. However, given the poor classification results, if skeletal remains do not contain a skull, which is commonly used to estimate population group (Hefner 2009; Spradley and Weisensee 2012), the greater sciatic notch should not be used to estimate population group.

In conclusion, geometric morphometric methods provide reliable sex classification when using dimensions or shape of the greater sciatic notch. Analysis of the sciatic notch provides more utility for sex estimation than other methods, given the notch is durable, clearly sexually dimorphic, and can be used apart from other pelvic features. It is not recommended to use notch dimensions for estimating population group, but notch shape may be of use in associating remains to a population group. Analysis of notch shape provides higher sex classification accuracies than notch dimensions, but both types of data provide reliable results.

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